Estimating the Effects of Toxicants on Ecosystem Services

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Numerous functions of ecosystems are essential to the quality of human life, including the provision of food, the decomposition of sewage, the provision of potable water, and the replenishment of breathable air. Although attributes of ecosystems directly of use to human societies are not the only ones worth protecting, emphasizing their services may be the most effective means of communicating risks of toxicants to the general public. However, although spatial and temporal scales of experiments to assess risk vary relatively little, actual spatial scales vary considerably, from local environments to global ecosytems. Generally, models are used to bridge these gaps in scale. In this paper, we examine ways in which toxicity test endpoints have been developed to describe effects of pollutants on essential ecosystem functions and the ways in which results are then extrapolated to scales that risk managers can use.
Key words: cumulative impact, ecosystem functions, integrated resource management, prediction, regional effects. *Environ Health Perspect* 102:936–939 (1994)

Human societies rely on certain essential functions of ecosystems that have operated with no or minimal human intervention. These "ecosystem services" are essential to the quality of human life (*1*) and include the provision of food, the decomposition of sewage, the provision of potable water, and the replenishment of breathable air (Table 1). If these functions are no longer performed by ecosystems, they must be replaced through human engineering or people will suffer. Because of their anthropocentric importance, these attributes of ecosystems are a logical focus of environmental management. There may be some drawbacks to an exclusively anthropocentric view of protecting ecosystem attributes; some people believe there is an ethical and moral responsibility to also preserve attributes important to other animal and plant species. However, if an activity has the potential to damage environmental attributes that are of value to human society, data on the vulnerability of these ecosystem services will provide a persuasive basis for making necessary choices between environmental protection and other economic and social goals.

The Scale of Ecosystem Services

People most easily appreciate ecosystem services and environmental problems (threats to or failures in ecosystem services) that are intense, local, and immediate. An example of an ecosystem service on this scale is the cool shade of a tree on a hot, sunny day. Landscape architects estimate that a 70-foot shade tree can mitigate 900,000 BTUs of heat; this is worth 3 tons of air conditioning that costs about $19 a day in the United States at $0.072/kW-hr (*2*). In addition, the tree provides erosion control, air pollution mitigation, aesthetic satisfaction, habitat, and recreational value. An example of the same ecosystem service on a slightly larger scale would be trees around a parking lot in Tampa, Florida, on a 93°F (34°C) day. These trees could make the difference between returning to a car at 150°F (66°C) or one at 80°F (27°C) (*2*). Increasing the scale of the example still further, the 10–20°F differences in temperature between cities and surrounding rural areas in summer (*3*) are attributed to combinations of great areas of heat-holding pavement and the relative lack of open water and plants for cooling. Of course, the ecosystem service of microclimate control is readily appreciated on a personal level.

However, as an ecosystem service or environmental problem becomes less intense, more widely dispersed, and occurs chronically, its perception directly or personally is more difficult. In addition, cause-and-effect relationships become less obvious, more uncertain, and, therefore, less likely to motivate action. Low-intensity stresses that cause subtle rather than obvious damage, damage that is spotty or thinly dispersed over a wider area, and damage that will occur only over the long term are all less obvious threats to human quality of life, harder to quantify, and less likely to motivate a management response. For example, in contrast to microclimate control, the ecosystem service of macroclimate control and the possible effects of a 2–8°F (1–4.5°C) temperature rise globally are not experienced directly, despite their cumulative and indirect importance.

Cumulative impact assessment recognizes that individually minor stresses can be significant when they are aggregated through time or space (*4*). As such, the scales on which various environmental problems are studied are not always sufficient to recognize cumulative environmental outcome (*5,6*). On the other hand, there are practical limits to the scale at which definitive and manipulative experiments on environmental problems can be conducted. Consequently, management decisions pertaining to problems affecting large areas or extended time frames must often be made on the basis of information that does not match the problem exactly in terms of stress intensity, time, and space. Extrapolations across scale are made to connect the responses that can practically be measured to the environmental effect of concern (*7*). This sets up a conflict. Only by expanding the scale of interest can the cumulative effects of human actions on ecosystem services be addressed. However, expanding the scale of interest depends on ecological models whose accuracy often cannot be definitively established (*8*).

The restricted spatial scale of many risk assessments has proven to be a shortcoming of many current management approaches. Because political, institutional, or management boundaries (e.g., countries or national forest districts) often do not overlap with ecological boundaries (e.g., biomes, ecoregions, watersheds), managers often can influence only a fragment of what is, biologically, a larger system (*9*). Each particular administrative unit is treated as "the only flower facing the sun" (*10*). This fragmented approach may result in various environmental problems being transferred from one administrative unit to another rather than being solved.

Fragmented management appeared to be effective when human population densities were low and technology was not energy intensive so that human society lay lightly on the ecological landscape. The last half of the 20th century has been characterized by a concomitant rapid destruction of natural ecosystems and a rapid surge in human population (*11*). As a consequence, pressures on the environment frequently became aggregated (or even continuous), and the insults increased both in intensity and proximity of one pressure to another. The inevitable result of this is multiple, closely spaced pressures on a lim-

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Received 2 February 1994; accepted 15 August 1994.

Table 1. An illustrative list of ecosystem services

Capture of solar energy and later provision of food, building materials, biomass-based energy
Decomposition of wastes
Regeneration of nutrients (e.g., nitrogen fixation)
Storage, purification, and distribution of water
Generation and maintenance of agricultural soils
Pest control (e.g., insectivorous birds, bats)
A genetic library for development of new products (food, pharmaceuticals, and other beneficial chemicals) through both Mendelian genetics and bioengineering
Maintenance of breathable air
Microclimate control and macroclimate control
Ability to buffer changes and recover from natural stresses such as flood, fire, pestilence
Pollination of agricultural crops
Aesthetic satisfaction

ited natural resource base (*5*). Optimizing the allocation of natural resources so that they will be available on a sustainable basis will require analyses on larger spatial scales, coupled with integrative, adaptive management strategies.

Adopting a landscape perspective coupled with integrative management will require trade-offs between ecosystems that have dissimilar attributes. An example of this problem in the United States at the national level is the disposal of New York City sludge. If, as it appears at the time this article was written, ocean disposal, especially in the coastal areas, is unacceptable, then should the sludge be placed on the plains of eastern Colorado, in the forested areas of New York state, in marshes and wetlands adjacent to the coastal regions, or on New York state farmland? The attributes of all four of these natural ecosystems (oceans, forests, high plains, and coastal marshes) are quite different; their sensitivity to waste materials is almost certainly different (and may vary depending on whether the wastes are organic or inorganic); and the time it would take for each degraded system to recover is almost certainly different. How can one develop a protocol or decision matrix that will enable one to choose the most ecologically sound and economically appropriate waste disposal option given the ecological differences that exist? Peddicord (*12*) provides an example of the conventional biological and chemical data that can contribute to this type of decision, but an integrated management approach demands that social and political considerations also enter into decisions about conflicting land use (*10*).

Toxicity Tests and Ecosystem Services

If decisionmakers are persuaded that ecosystem toxicity tests are useful in ensuring the delivery of ecosystem services on a large scale, such tests will be developed. As always, tests at early stages of development will be difficult and uncertain. That is simply a fact in all sciences, not just toxicity testing. The most developed methods for toxicity tests of ecosystem services are those at a local scale and those assessing effects on biomass production related to agriculture, forestry, and fisheries industries (see Table 1). Small-scale toxicity tests on related services (e.g., pollination of agricultural crops; see Table 1) are also relatively well developed. It is estimated that 30% of the food consumed in the United States depends on pollination by bees, and this ecosystem service is worth \$8–40 billion per year (*13*). Toxicity tests on honeybees have been used for pesticide registration under the Federal Insecticide, Fungicide and Rodenticide Act (*14*). However, experience is less extensive with toxicity tests related to the other 10 ecosystem services listed in Table 1 or with those dealing with stress on larger spatial scales (Table 2).

A few examples of studies examining the effects of toxicants on ecosystem services at different scales are summarized in Table 3, though this list is by no means exhaustive. There are many small-scale toxicity tests on single species. However, although studies of stress effects on crop yields are common, spatial scales of tests vary relatively little, whereas spatial scales of the underlying problems vary considerably, from local environments to global ecosystems (Table 3). In addition to toxicity tests, synoptic surveys are used to determine the association between ecological conditions and levels of toxic substances. Many natural systems are observed and the relationships between ecological and chemical conditions determined. Models bridge this gap. The citations in Table 3 illustrate ways in which environmental problems have been matched to scientific observations from either toxicity tests or other synoptic survey data and the results extrapolated to scales having significance to managers. For example, Baker et al. (*15*) evaluated the effects of carbon dioxide on rice growth and yield on a local scale, while Bachelet et al. (*16*) extrapolated from small-scale tests to yield projections on global stress. Similarly, Aber et al. (*17*) report results of large-scale experiments examining air pollution effects on nutrient cycling in a forest. This information is integrated with other sources of information through geographical information systems to develop a predictive model for regional effects (*18*).

In these and other cases, the way in which toxicity test data are extrapolated to larger spatial scales and longer time frames is more demanding than assembling the database itself (*8,19,20*). When designing tests to measure toxicity of wastes to ecosystem services, the closer the observations are to the property of interest, the less the uncertainty. When the pollution problem is on a small spatial scale, toxicity tests similar in scale are possible. However, it is impossible to manipulate large, replicated systems to test definitively for effects on regional scales. Models are vetted methods for making predictions on a scale that is most relevant, but on a scale at which toxicity tests are impractical. As Barnthouse (*8*) points out, models are not "cheap substitutes for data." Combinations of concentration–response models from toxicity tests combined with mapping techniques seem particularly useful in extrapolating from spatially limited toxicity tests to regional predictions of toxic effects (*21*). Extrapolations from short to long time frames depend largely on space-for-time substitutions (*22*).

Endpoints for assessing some components of ecosystem services and models for regional extrapolations have only recently been developed and have not been examined under conditions of toxic stress. For example, the maintenance of breathable air and macroclimate control depend on gas exchanges between terrestrial systems and the atmosphere. The effects of warming on these exchanges have been determined (*23*). Effects of toxicants on denitrification in soils have been examined (*24*), and regional models of denitrification of forest soils have been developed (*25*). Combinations of such types of information may facilitate the estimation of toxicant effects on ecosystem services. Similarly, the cumulative effects of wetland loss or degradation on water quality have been modeled (*5*), and pollutant effects could be incorporated into models of this sort.

Of course, ecological models are accompanied by considerable uncertainty; this is an undesirable but inevitable part of the extrapolation needed to examine larger

Table 2. Examples of stresses at various scales

Scale	Example
Local	Heavy metal pollution Oil spills
Landscape	Air pollution Pesticides Fertilizers/nutrients
Regional	Air pollution Salinization
Continental	Acid rain UV-B penetrance
Global	Increases in atmospheric CO_2

Table 3. Some examples of studies on toxic effects on ecosystem services at different spatial scales[a]

Toxicant	Scale of Stress	Scale of Observation	Scale of Prediction	Study summary
Biomass production				
Heavy metals	1	1	1	Fly ash application reduces the yield of alfalfa (*27*).
CO_2	1	1	—	Rice yield increased when ambient CO_2 increased from 330 to 660 ppm (*15*).
CO_2, UV-B	5	1	5	A model for predicting rice yield based on dose–response data, mapping, and simulation models for exposure (*16*).
Acid rain	4	2	4	Linked geographic information on deposition rates, seasonal conditions, and natural buffering capacity to define regions most likely to be affected by acid rain. About 45% of the surface waters in eastern Canada are at risk (*28*).
O_3 air pollution	2	2	—	Forest damage typical of ozone exposure examined using remote sensing; tying together information obtained on three spatial scales; controlled laboratory toxicity tests, local surveys of foliar damage, and regional assessments through remote sensing (*29*).
Decomposition of wastes				
Industrial waste	1	1	1	Total organic carbon removal by microbial communities from publicly owned treatment works fell with the addition of toxic effluents (*30*).
Regeneration of nutrients				
NO_x air pollution	3	3	—	Forests responded to 3-year additions of nitrogen with increased net primary production. Soil organic matter acted as a sink for nitrogen additions. But following saturation there is increased leaching into aquatic systems (*18*).
Storage, purification, and distrubution of water				
NO_3 fertilizer	3	2	3	Linked crop maps, recommended fertilizer application rates, aquifer and susceptibility maps using a geographical information system. Predicted that 24% of land area in Texas has a high potential for groundwater pollution from current agricultural practices (*31*).
Generation and maintenance of agricultural soils				
Herbicides	1	1	1	Common herbicides inhibit the breakdown of plant litter, yet accelerated nutrient losses (*32*).
Pest control				
Pesticides	2	2	—	Cypermethrin applied to control lepidopteran forest pests also reduced the reproductive success of a natural predator of the pest, the blue tit (*Parus caeruleus*) (*32*).
Genetic library				
Acid rain	3	1	3	Linked regional chemical and biological effects models and predicted that 55,000 lakes in eastern Canada had lost at least 20% of their biotic diversity (*34*).
Maintenance of breathable air and climate control				
NO_x air pollution	2	2	—	Nitrogen additions decreased the methane consumption of forest soils (*35*).
Ability to buffer changes and recover from stress				
Smelter pollution	2	2	—	Forests affected by smelter pollution took longer to recovery from natural fire disturbances (36).

[a]Spatial scale is ranked from 1 to 5. 1 = local; 2 = landscape; 3 = regional; 4 = continental; 5 = global. When no explicit extrapolation was made, no scale is assigned (—).

scales. The only alternative to uncertainty is to allow damage to occur. Yet, given the value and irreparable nature of some ecosystem services, this is an unacceptable option in many cases. For example, assessing the disaster at Chernobyl after the fact has increased the knowledge of the environmental effects of nuclear radiation by many orders of magnitude and greatly reduced the uncertainty of any subsequent predictions of environmental outcome. It seems that preexisting models of the uptake of radionuclides by food crops were fairly accurate, while models of human uptake through food and damage to pine forests greatly overestimated effects (*26*). Did the previous uncertainty warrant any lack of protective action? Probably not. Explicit estimates of uncertainty provide managers with an index of the quality of their information. Uncertainty is then considered along with other information (options, costs, magnitude of possible outcomes) and their uncertainties in making management decisions. Management can proceed with uncertainty.

Going Beyond Toxicity Testing

Even after the most robust toxicity tests using ecosystem services as endpoints or thresholds are produced, some ethical questions remain for society that will not be resolved by scientific evidence. These are questions that are not amenable to resolution by science because they are primarily value judgments. For example, suppose that ecosystem services deemed valuable by human society can be delivered at toxicant concentrations that cause loss of a species. Is this biotic impoverishment acceptable if the ecosystem services are unimpaired? There are undoubtedly many species whose functional role in ecosystems is probably marginal, if only because of their low numbers. For example, does the California condor now play a significant role in recycling carcasses in local ecosystems? Probably few ecologists would say that it does, and even those who say that the species does have a significant role would find it difficult to quantify. Keep in mind that the question is not "could it play a significant role at the right population density" but "will it do so under conditions now existing or likely to exist in the near future?" Nevertheless, for many, the aesthetic value of this endangered species might be on a par with more utilitarian services. Society may have an ethical responsibility to preserve and improve conditions for species that have no demonstrable utilitarian purpose but that may have aesthetic and social value.

Summary

Risk assessment procedures that incorporate information on the effects of toxicants on ecosystem services are likely to provide a persuasive basis for making environmental decisions. Although attributes of ecosystems directly of use to human societies may not be the only ones worth protecting, focusing on them may be the most effective means of communicating risks to the general public and may prove to be closely associated with other attributes whose value is recognized by a smaller segment of society. While toxicity tests with ecosystem services related to agriculture, fishery, and forestry industries are common, toxicity tests related to other ecosystem services are less developed, as are methods for extrapolating to regional and global spatial scales. In addition, while there is an inescapable conflict between the desire to have evidence that is reliable and the desire to have evidence that is relevant, management can proceed with calculated uncertainty.

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